THE EFFECT OF SUPERGLACIAL DÉBRIS ON THE ADVANCE AND RETREAT OF SOME CANADIAN GLACIERS.

OBSERVATIONS on rates of motion, amounts of advance or retreat of glaciers, and kindred statistics are now being collected from all quarters of the globe in the hope of deducing some general laws of ice-motion in the present, and of throwing some light on glacial conditions in the past.[1]

Obviously the advance of glaciers is influenced by two factors: (1) rate of motion, and (2) rate of waste. Any cause increasing the rate of motion will tend to push the front of the ice forward, and this advance will be held in check only by the amount of waste. Waste will be increased either by a rise in temperature, producing increased melting and evaporation, or by increased exposure to dry air producing evaporation. A glacier may advance, therefore, either from increased motion or from decreased waste.

Observations on the advance or retreat of existing glaciers have been correlated almost exclusively with the factors influencing rate of motion. The rate of waste is usually neglected, or is regarded as of secondary importance. Of secondary importance it may be in the case of any one glacier, since the daily and annual ranges in temperature about the freezing-point are approximately the same in successive years. Hence it may be safely assumed that the amount of water lost by any one glacier will differ from year to year mainly in proportion to changes in the mass of the ice, which in turn is affected by rate of motion. But when different glaciers are compared, it becomes evident that rate of waste is an important factor in determining the position of the ice-front.

Glaciers differ from each other in rate of waste, as they do in rate of motion, and a sluggish glacier, slow-moving and slow-wasting, may advance farther than one whose rate of motion is faster, but whose rate of waste is also faster.

[1] HARRY FIELDING REID, JOURNAL OF GEOLOGY, 1895 to date.

The several factors influencing the rate of melting will be discussed later. The one which it is especially desired to emphasize is the protective effect of a thick covering of débris.

It is a familiar fact that dust absorbs the sun's heat, causing melting, with the formation of dust wells, while larger fragments shade the ice, and may be left standing on protected pillars, the ice having melted around them. Sand and débris cones are formed in the same way, from the shading of the ice by a pile of material. Obviously, if this process were carried to an extreme, and the entire surface of the ice covered, the whole would be shaded, and hence protected from melting.

In regions where glaciers now occur (i. e., regions of high altitude or of high latitude) there are great contrasts in temperature between sun and shade. It frequently happens that this contrast involves a range above and below 32°, and that the temperature is below freezing in the shade when it is well above in the sun. A débris covering will protect a glacier from the direct sunlight, and may therefore keep its temperature below 32°, and so prevent melting.

Moreover, the daily range in temperature at the surface of the soil is much greater than the daily range slightly below the surface. A point below the surface will be shielded from extremes and will be colder during hot, and warmer during cold, hours, than the surface. In the case of glaciers, a débris covering protects the ice from the air of the surface. Hence in times of extreme cold the protected ice will be warmer than the surrounding air; in times of heat it will be colder. Since in regions where glaciers now exist, the yearly temperatures below 32° are greater in number and in amount than those above, this protection from the air will be of more avail to prevent melting than to cause it.

It is therefore to be expected that protected glaciers should advance farther down their valleys than if not so protected, and that the retreat of protected glaciers would be slower.

In the mountain region of British Columbia and Alberta there are many hundred existing glaciers. This region is one of especial interest to the glacialist in that it appears to be the center from which came the lobes of a large part of the Cordilleran ice-sheet. The highest parts of the mountains were never covered by ice, nor

does there seem to have been formerly any common direction of movement. In the past, as at present, glaciers moved toward all points of the compass, and the present glaciers may be regarded as the actual remnants of the upper portions of the great glaciers of the past.

The Canadian Pacific Railway affords easy access to many of these glaciers. It crosses the mountains near the fiftieth parallel, and at this point the glaciers are confined to a belt about one hundred miles wide, within the Rocky and Selkirk ranges.

The valley glaciers near the line of the Canadian Pacific may be classified into two groups. These groups are primarily geographical, being respectively east and west of the continental watershed, but the glaciers of these two groups have striking physical differences also.

GLACIERS OF THE CENTRAL AND EASTERN ROCKIES

The valley glaciers of this region have little or no névé portions, being fed by avalanches from overhanging cliff glaciers. These avalanches carry down great quantities of bowlders, mixed with the ice and snow, with the result that glaciers of this type are covered throughout almost their entire length with a thick mantle of débris. The cliff glaciers have névé portions, but the topography is such that large snow-fields do not accumulate. The cliff glaciers rest on exceedingly steep slopes, usually terminating upward in arêtes, so there is little place for the accumulation of snow. It is characteristic of this region that its glaciers consist of an upper névé and cliff portion with very high gradient, separated by a fall from a lower débris-covered valley portion.

GLACIERS OF THE WESTERN ROCKIES AND SELKIRKS

These glaciers have very large snow-field and névé regions, and such material as they carry is largely subglacial or englacial. In their method of formation these glaciers resemble the typical valley glaciers of Switzerland, but differ in that they are proportionally broader and shorter. In this region one névé may feed many glaciers, whereas to the east many cliff glaciers feed a single valley glacier.

Of late years Messrs. George and William S. Vaux[1] have recorded

[1] GEORGE AND WILLIAM S. VAUX, "Observations on Glaciers in British Columbia," *Proceedings of the Academy of Natural Science*, Philadelphia, 1899.

observations on the Illecillewaet, or great glacier of the Selkirks. Their observations include a measurement of the rate of motion of different parts of the ice by means of iron plates fixed on the surface, and also a record of the retreat of the ice front since 1887. They record a few observations on other glaciers, but these are of a more general character. In 1888 Dr. William S. Green made a single measurement of the rate of movement of the Illecillewaet.[1]

These observations appear to be the only ones on record. In the face of such sparse statistics, generalizations seem premature;

FIG. 1.—Victoria Glacier, showing level surface, and cliff glaciers on Mount Lefroy.

nevertheless, one fact is evident, namely, that the glaciers on the east, which are covered with débris, are either advancing or retreating slowly, while those on the west, with clean surfaces, are retreating rapidly.

GLACIERS OF THE FIRST GROUP

Victoria glacier (*Fig. 1*).—This glacier is now well known to tourists, lying at a short distance from one of the Canadian Pacific Railway châlets, and being the feeder of the now famous Lake Louise. As seen on the map (Fig. 2), it is short and wide, and has two branches, which come from the south and the east repectively. These branches are fed by avalanches from the cliff glaciers of

[1] GREEN, *Among the Selkirk Glaciers* (Macmillan, 1890).

Mounts Victoria, Lefroy, and Aberdeen, and except in its upper portions, the glacier is covered with débris. The glacier is nearly flat, and each of its upper ends entirely fills its valley. Snow and rock from avalanches form a heterogeneous pile on the surface, snow predominating at the ends and the sides of the upper portions. This snow is rapidly melted by the heat of the sun, and a short distance from the upper ends is a region of small ice pillars. As the lower end is approached, surface débris increases, until at the extreme

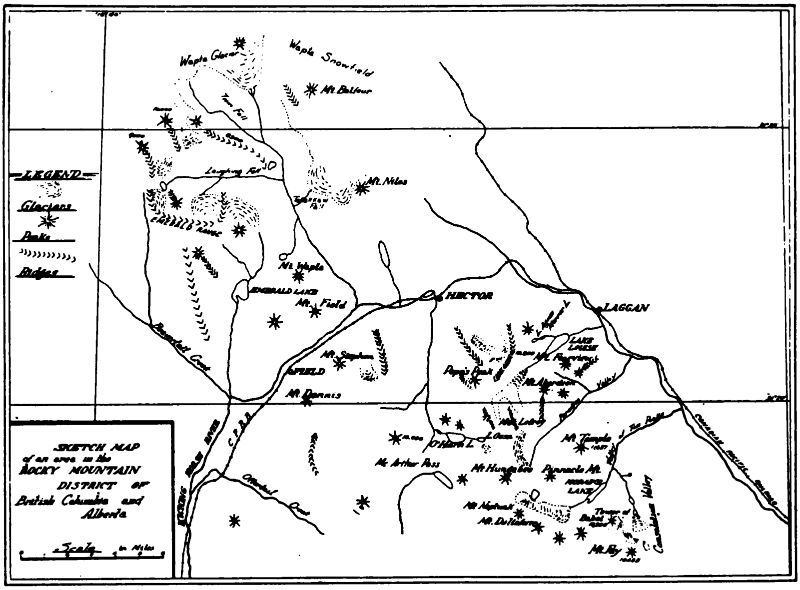

FIG. 2.—Sketch map of area referred to in text.

end it is in most places impossible to tell where the ice ends and moraine begins.

In recent geological time this glacier was evidently of much greater extent, but in the immediate past it extended only a short distance farther than at present. It has left a series of recessional moraines, but these are close together, often crossing or ramifying. Closely bordering this recessional belt are fair-sized trees, and beyond these trees no moraine is found. Glacial material is abundant throughout the valley, but beyond the moraines it is in a secondary position, deposited by water. Of late, therefore, the glacier has retreated but little.

It is a notable fact that the Victoria glacier does not face directly down its valley, but diagonally across it, the ice-front facing the northwest. The high cliffs of Aberdeen keep off the early morning sun, so that even in midsummer the sun does not strike the glacier before 7:30 A. M., and then at first only the northwest side. The direction faced by the ice-front is thus determined, not by the direction of motion, but by the position of maximum melting.

As already stated, the end of the ice is mainly buried in moraine, but at two points ice is exposed. At both points the face is steep,

FIG. 3.—Front of Victoria glacier, showing its steep face, diagonal position in the valley, and terminal moraine.

exposing the laminæ of ice. In this respect it resembles high-latitude glaciers, rather than the usual alpine type (Fig. 3).

The surface of the Victoria glacier is very flat, the angle of profile rarely exceeding 8°. This flat surface makes an angle with the steep front somewhat exceeding a right angle.

During the year from July, 1899, to July, 1900, Mr. Vaux found that a marked bowlder in a central position on the ice moved 147 feet. One at the edge moved 115 feet. Shrinkage for the year was only 6 feet.

Glacier of the valley of the Ten Peaks.—This glacier occupies a valley parallel to that of the Victoria glacier, some ten miles to the southeast. Moraine Lake lies in this valley a short distance below

the glacier, the glacier itself being confined to the southeastern side of the upper end of the valley. This glacier closely resembles the Victoria, but has a few points of difference. The cliff glaciers which feed it are on the southeastern side of the valley. Opposite these cliff glaciers, on the northern side, are talus-covered slopes. The talus also apparently occupies a portion of the valley bottom, and here meets some old and very angular débris. A small lake occupies the valley bottom at an elevation of about 7,000 feet. It is surrounded by talus and débris on three sides, the fourth being the rock of Mount Pinnacle. This lake appears to be fed by a subtalus inlet, the greater part of its water coming from the side of the glacier. This glacier, then, is fed not only at its end, but from its southern side, and water issues not only at its front, but at points along the northern side.

Its surface is covered with débris more deeply than that of the Victoria glacier. The rock masses are remarkably angular and often of great size. In several places piles of débris have accumulated, protecting the ice beneath and forming rock cones.

This glacier is remarkable in that it is advancing, both down the valley and also laterally on its northern side. For the lower mile of its course it is now overriding a large forest. Unfortunately, no data are on record concerning its rate of advance or its rate of motion.

In a pamphlet on glaciers Mr. Vaux remarks concerning this glacier: "At some date, not very remote, an unusual avalanche of rocks of enormous proportions has buried the ice deep in piles of huge stones and bowlders which, preventing the access of the sun's rays, protect it from much melting." It is hardly necessary to postulate an *unusual* avalanche. The cliffs south of the glacier are tremendous, and the rock, a thick-bedded limestone, weathers along its joint planes into large rectangular blocks which are continually falling to the glacier below. In this weathering process not only the cliff glaciers, but also gravity and the great daily range in temperature, are effective.

The fact that the glacier fills only the southern part of its valley seems due to the same cause that leads to the diagonal fronting of the Victoria glacier. The ice is shaded by high cliffs on the east and

south, and when the morning sun finally strikes it, the first portion to be touched is the northern side. This glacier also has little fall, and its front is steep. Its valley is terraced and shows evidence of occupation by a great glacier in the past, and Moraine Lake is held up by a débris dam; but there are no modern terminal moraines other than the one now being formed. This glacier, therefore, is larger at present than at any very recent time. It is a significant fact that this glacier, which is advancing, should be much more deeply covered with débris than other similar ones which are retreating slightly.

FIG. 4.—Front of glacier in Consolation Valley, showing its steep face, and terminal moraine in the lake.

Glacier in Consolation Valley.—Consolation Valley is the largest tributary of the valley of the Ten Peaks. It is similar to the two preceding valleys in the presence of lakes in the lower part of its course, and of a débris-covered glacier at its head. This glacier seems to be little visited, and was omitted entirely from the Canadian survey map (Lake Louise sheet, 1902).

The trend of the valley is northward; consequently the glacier is not shaded in the early morning. As a result, it faces directly down its valley. At its upper (southern) end this glacier begins in two alluvial cones which meet from opposite sides of the valley. It is fed mainly from its southwestern end and side, from cliff glaciers on Mount Fay (Fig. 4). Cliffs bound its southwestern side, and from these cliffs several alluvial cones extend, in some cases reaching the ice and loading it with material. The consequence is that the glacier is streaked with ridges of material of various kinds and colors, according to the source. These ridges bear a general resemblance to

medial moraines. Between the ridges the ice is comparatively clean and has melted so that the débris stands up on ridges of ice.

A remarkable feature of this glacier is the presence of several lakes on the ice. Their basins apparently began as transverse crevasses, and grew by melting. Their walls are vertical, and display the synclinal structure of the ice, with the drift covering on the surface. There are several lakes in various stages of growth, the process being that of melting away beneath, the top being shaded by débris, and the result being the production of a nearly round lake from a long narrow one. The largest of these lakes measured about 500 feet by 300 feet.

FIG. 5.—Lake on the ice of the glacier in Consolation Valley, showing the synclinal structure of the ice and the débris covering.

Débris was constantly falling into this lake. The layers of ice could be plainly seen (Fig. 4). The lamination was due mainly to differences in consistency of the ice. The amount of interbedded material was small, but was all concentrated along definite layers.

The lower end of this glacier was more completely covered with débris than the upper part, the streaks of different colors being pushed close together. The glacier ends in a lake, a nearly perpendicular cliff of ice rising from the water. Here also the layer of ice may be seen (Figs. 5 and 6).

One recessional moraine is present, extending in a peninsula from the shore of the lake into the water. On the shore the northern edge of this moraine is bordered with bushes, and there are no other recent moraines. It is therefore evident that this glacier is only a few feet shorter than at the time of its recent maximum extension.

Features common to the preceding glaciers.—These glaciers each have a main line of drainage coming from beneath an arch of ice, but only a portion of the drainage comes directly into this channel. Water escapes through the bordering débris at the front and sides, and can often be heard trickling beneath the drift. The subglacial drainage of the Victoria glacier has been changed, a long cave showing the position of a former exit. No superglacial drainage was observed.

It is characteristic of all of these glaciers that their gradients are

FIG. 6.—Glacier in Consolation Valley.

low; that their centers are but slightly higher than their sides; that their fronts are nearly vertical; and that of late they have retreated little, if at all. The cliff glaciers which feed them are 2,500 feet or more above the level of the valley glaciers below, and the lower limit of the glaciers is at about 6,000 feet.

The material with which their surfaces are covered is angular and talus-like. It is frequently stated that superglacial material is highly oxidized, and that by this characteristic it may be distinguished from subglacial material in the deposits of the glacial epoch.

Among the glaciers of the eastern Canadian Rockies the superglacial material accumulates by falling on the ice in steep, narrow valleys, as in the instances just described. In no case was the amount of oxidation found to be extensive. It was usually apparently less

than in ordinary talus slopes, for in falling 2,000 feet or more the bowlders often break and gain unweathered surfaces. But in shape there is a conspicuous difference between subglacial and superglacial fragments. The superglacial material retains its angular form, and is dropped in the terminal moraine without scratches, while the subglacial material is worn and grooved. The result is that those parts of the moraine which are composed of superglacial débris resemble talus, and can be distinguished from it only by their topography.

FIG. 7.—Cliff glacier of Mount Victoria, and the side of the Victoria glacier.

The glaciers described above represent the type in this region. Several other glaciers of the same type were seen by the writer, but only one of them lay west of the continental divide. This one is at the head of Lake Oesa.

The steep front characteristic of these glaciers is a feature that has hitherto been recorded only in the case of high-latitude glaciers. Steep fronts are characteristic of both cliff and valley glaciers in the Canadian Rockies, and are due to different causes in the two cases. In the cliff glaciers the steep front of the ends comes from the periodic breaking off of the front of the glacier, the broken end falling over a cliff and leaving a vertical ice face on the glacier (Fig. 7). It occasionally happens that the slopes of mountains on which cliff glaciers rest are bounded by cliffs on several sides. In such cases the cliff glaciers

may acquire steep sides as well as steep ends by this breaking off process. When the rock sides are higher than the floor beneath the ice, the sides of the cliff glaciers are buried in snow, and so, either actually or apparently, are not steep.[1] In the valley glaciers the steep end has some other cause which appears to result from a combination of shape and manner of melting.

FIG. 8.

These glaciers of the central and eastern Rockies remain approximately constant in thickness, melting on the surface at their upper ends, and beneath the surface at their fronts. The regions of accumulation and of maximum surface melting are similar. Fig. 8 shows diagrammatically the front of one of these glaciers. The upper layers are protected from melting, hence remain intact at the front, while the melting of the lower layers leads to the formation of a cliff and of an angle between surface and front. Glaciers of the ordinary alpine type push forward, at a high gradient, from a region of perpetual snow, melting at the surface and thinning toward their lower ends. Fig. 9 represents the front of one of these glaciers. The end slope may be as steep in the second case as in the first, but there is invariably the difference that among these glaciers there is a gradual curve from surface to end, while among those of the first group there is a sharp angle between a nearly horizontal surface and a nearly vertical front. The slope of the front of the second type of glaciers is determined in part by the gradient of their beds, in part by the rapidity of surface melting at the front. Among glaciers of the first type, slope and surface melting are both at a minimum, and the angle of the front is determined by rate of sub-surface melting.

FIG. 9.

Steep sides as well as steep ends are characteristic of high-latitude

[1] Cliff glaciers were defined by Salisbury in this JOURNAL, 1895, p. 888. The cliff glaciers in Alberta are of a slightly different type from those described from Greenland. They form in essentially the same way, but the ends of the Canadian cliff glaciers usually push over the ends of precipices and break off, leaving several hundred feet of vertical ice which forms an ice-cliff above the rock cliff. Those figured by Salisbury appear to end like steep alpine glaciers. Another point of difference is that these Canadian cliff glaciers lie on the general slope of the mountain and are much broader than they are long, while those in Greenland lie in steep gullies.

glaciers. Among the eastern Canadian glaciers the sides are almost invariably buried either in talus from cliffs or in moraine (Fig. 7). Among the glaciers above described the glacier of the valley of the Ten Peaks, which is advancing laterally, is the only one in which the ice of a side was visible. In this case the side was steep, like the front.

GLACIERS OF INTERMEDIATE CHARACTER

It is impossible to draw a hard and fast distinction between these two types of glaciers, since there are many glaciers, parts of which belong to one type and parts to the other. But in each case it was evident that whenever glacier ice was buried sufficiently to shut out sun and air entirely, surface melting practically ceased.

The Yoho Valley lies on the western side of the continental divide. Though a tributary by name, it furnishes the greater part of the water supply of the Kicking Horse River. The Yoho Valley is a glacial canyon, with rock terraces on its sides. There are six large glaciers on the sides of the Yoho Valley, the water from these glaciers coming over the terraces in falls. One important tributary enters the Yoho from the west. At its junction with the Yoho this tributary forms the Laughing Fall; farther up its course five glaciers lie on its sides.

The glaciers of the Yoho are fed by large snow-fields, for the most part yet unmapped. As a rule, the surfaces of the glaciers are steep, clean, and much crevassed, and their ends have the gradual curve from surface to front illustrated in Fig. 9. The sides of the valley are so steep that the fronts often have a high angle, and ice cascades occasionally occur.

Most of these Yoho Valley glaciers belong to the second type, but three of them combine the characteristics of the two groups. These three lie on the sides and end of Laughing Fall Valley.

One of these glaciers on the north side of Laughing Fall Valley enters its basin over a col between two limestone peaks. Its general direction of flow is eastward over the col; then it cascades over a cliff forming some fine seracs, and turns southward toward the Laughing Fall Valley. The eastern slope of the basin of this glacier, is formed by shale ridge locally called "The Whaleback." The ice, in turning the corner just described, banks itself up against "The Whaleback" and becomes buried in shale. With the shale are mingled rounded limestone fragments from the peaks to the west, the débris being

frozen into the ice and forming a sort of conglomerate. The surface is thickly covered also. The ice thus loaded and protected seems entirely stagnant, neither moving nor melting. The main body of the ice, however, was clean-surfaced. Several recessional moraines showed its retreat.

Similarly a glacier extending northward from Emerald Mountain showed several recessional moraines on its western side, while the eastern portion, which was buried in talus, appeared to be stationary.

At the head of this same Laughing Fall Valley lies a lake, about a mile in length. Its outlet is over rock, its eastern and northern sides are of rock, while its western side is formed by a débris-laden glacier. Besides the ice is a brook, the lower course of which is arched over by snow. The snow patch ends in the lake, and portions of it break off and float away like small icebergs. The glacier appears to be advanced as far as it ever was. There is no moraine in front of it, and no débris could be seen in the water of the lake. Since the water of the lake is remarkably clear, any débris that had been dropped in it could have been distinguished.

The débris of this glacier is apparently derived directly from the mountain behind it, without the assistance of cliff glaciers. This point, in which these three Yoho glaciers are alike, is an important difference between them and the glaciers of the first group. Although resulting in a preservation of the ice in both cases, it is in the Yoho an exceptional and unusual occurrence, while among the glaciers first described the débris covering comes as a necessary part of their mode of origin.

The Lake Louise sheet of the Canadian Survey map, though accurate near the railroad, is in the Yoho Valley entirely a work of imagination. The lake at the head of Laughing Valley, and five large glaciers are omitted entirely, while the position of mountains and slopes of valleys are inaccurate. The sketch map (Fig. 2) accompanying this paper is adapted from this sheet.

GLACIERS OF THE SECOND GROUP

Glaciers of the Yoho Valley.—At the head of Yoho Valley is the Wapta glacier (Fig. 10). This glacier is fed by a great and yet unmapped snow-field. The glacier itself is broad and short. Its

slope is steep; its surface clean and much crevassed; its front, though steep, does not exhibit a cliff.

No records are available as to its rate of motion, but a rapid retreat is evident. Drift material, free of vegetation, is to be found for about three-quarters of a mile from the ice and extending 300 feet up the sides of the valley. The ice descends to a level of 5,000 feet (aneroid).

FIG. 10.—Wapta glacier.

Fed by the same snow-field is another glacier which descends the valley above Twin Falls. This valley is flat and open, the glacier having less slope than the Wapta, and for some reason which is not evident the ice-front does not descend below 5,700 feet. A recent rapid retreat is evident, but the exact amount could not be determined, since fresh landslides have brought down much material which has been mingled with the drift, while both drift and talus are being worked over by the glacial stream.

The Illecillewaet glacier.—Probably the most famous and most often visited glacier in British North America is the Illecillewaet, or

Great Glacier, of the Selkirks (Fig. 11). At a distance of only two miles from the railroad, the glacier is easily reached by a good trail.

It is fed by a snow-field which forms a plateau at a level of about 7,000 feet. From this névé the glacier descends in a great ice cascade to a level of 4,750 feet. Its surface is perfectly clean and much

FIG. 11.—Illecillewaet glacier.

broken, seracs and crevasses being abundant. Its front is very little steeper than the average slope of the glacier.

In 1888 Dr. Green found that in twelve days the center of the ice moved 20 feet; the side, 7 feet.[1] Since 1887 Messrs. George and William S. Vaux have made a special study of this glacier. The general average of their observations shows a motion of from 6 to 2 inches daily in different parts of the ice. The great difference between these figures and Dr. Green's may be due to some change in conditions, or to the observations having been taken on different parts of the ice. At all events, Dr. Green's figures seem too high

[1] *Among the Selkirk Glaciers* (Macmillan, 1890).

for the present motion. Since the beginning of the observations of Messrs. Vaux the end of the glacier has been receding rapidly. A general average of their observations gives an annual recession of about 60 feet.

The Illecillewaet névé is some 10 square miles in extent. It lies in a depression between several high peaks, and feeds four large glaciers. A second of these is the Asulkan. During the year 1899–1900 Mr. Vaux reports that this glacier receded 24 feet, but at present it seems to be advancing. When I visited it this summer, the end had pushed forward up and over an old moraine.

The Asulkan and Illecillewaet glaciers are roughly parallel, both moving north. From the same névé comes the Geikie glacier, moving southwest, and the Deville glacier, moving east. There are several lesser, unnamed glaciers at intermediate points. All present the same general characteristics of high gradient, clean surface, and rapid retreat.

CONDITIONS AFFECTING MOTION

Without entering into the causes of glacier motion, it is safe to say that the conditions favoring rapid movement are steepness of slope, great precipitation of snow, little load, and high temperature.

Slope.—The slope is greater in glaciers of the second type than in those of the first type. The Victoria, Ten Peaks, and Consolation Valley glaciers on the east side are almost flat. They appear to lie in valleys of slight declivity, and the continual melting at their upper ends keeps the ice of nearly uniform thickness. But glaciers of the second group have, as a rule, great slopes. The Illecillewaet rises over 2,000 feet to its névé, in a distance of about two and one-half miles. The Wapta is almost as steep, rising about 1,200 feet. The Asulkan has a varied course, having two falls separated by a flatter area, but its general slope is steep. This steepness of slope is due partly to steep declivity of the valley floors, partly to great thickness of the ice in the region of accumulation, with thinning from melting in the region of dissipation. Both from steeper slope of the valley and from greater pressure of a thicker mass of ice above the glaciers of the second type have the advantage.

Snowfall.—Records are kept at the Glacier House with more or

less regularity. The station is nearly 3,000 feet lower than the Illecillewaet névé. The amount of precipitation received by the glacier is therefore probably greater than that of the valley. An average of seven years' observations gives an annual snowfall of 36 feet and 5 inches.

No records are kept in the immediate vicinity of the Rocky Mountain glaciers. Records here would be of less significance, for precipitation is exceedingly local in character. Moreover, owing to the occasional occurrence of Chinook winds, there is far greater evaporation than in the Selkirks. It is safe to say that here, as elsewhere in the Rockies, there is far less precipitation than among the mountains to the west, and that there is more evaporation.

The prevailing winds coming from the west and from the sea, the moisture is first precipitated on the westernmost mountains. As they progress eastward, the prevailing winds have less moisture. Having less moisture, the daily range in temperature becomes greater, and the difference in temperature and in precipitation between valley and mountain slopes, greater. In the Bow Valley, near the glaciers of the first group, the maximum depth of snow in winter is said to be 2 or 3 feet; on the slopes near the glaciers of the same region, 10 or 15 feet. The depth of snow on the ground in the Selkirks, near the Glacier House, is 20 feet or more.

Load carried.—It has been shown by I. C. Russell,[1] and also by Messrs. Chamberlin and Salisbury,[2] that glaciers heavily loaded with débris move more slowly than those which have no load. This is due in part to the lessening of the viscosity of the ice by the introduction of rigid material, and in part to the formation of débris-charged ice-dams at the ends, which hold back the advancing ice. So far as could be observed, the amount of englacial material is small in both types of Canadian glaciers, and there is probably little difference in viscosity from this cause. But it is common for the glaciers of the first type to end in a mass of ice thickly charged with débris and forming a sort of ice conglomerate. This was the case also with the three débris-charged glaciers of Laughing Fall Valley;

[1] JOURNAL OF GEOLOGY, Vol. III (1895), pp. 823–32.

[2] *Ibid.*, 1894–95.

but only in one instance, the side of the Illecillewaet, was it evident among glaciers of the second type.

Thus all the conditions affecting rate of motion are in favor of the glaciers of the second type. They have greater slope, more snowfall, and less retarding load. According to the very meager statistics, their rate of motion is about five times as rapid as that of the glaciers of the first type.

CONDITIONS AFFECTING WASTE

Since, therefore, the glaciers of the second type are retreating with much greater rapidity than those of the first, more waste must be looked upon as the cause. The factors which affect rate of waste may be summed up under (1) amount of rainfall; (2) daily and annual range of temperature above the freezing-point; (3) altitude of the snow-line; (4) topography; (5) amount of sunlight and of air received by the ice.

Rainfall.—The records at the Glacier House show an annual rainfall of 12.98 inches. This amount is too small to be a large factor in wastage, especially when contrasted with the great snowfall. The only records kept in the Rocky Mountains localities are notes of the number of rainy or showery days. These notes show considerable variation in different years, but afford no data for comparison with the western region.

Range of temperature.—For the past seven years records have been kept at the Glacier House. From the end of October until the beginning of March the maximum temperature is below freezing. In March, April, September, and October the average temperature is near the freezing-point, either above or below. In the summer months it is above, with an absolute maximum of 86°. The daily range is 10 to 20°.

At Banff records are kept in the office of the Rocky Mountains Park of Canada. There is much more variation in temperature here, and the daily range is greater, and sometimes involves a rise above the freezing-point in winter. In midwinter temperatures of +40° are not uncommon. The daily range is from 20 to 40°, and sudden intense cold may be followed by warm Chinook winds.

The two climates are in a general way similar. Winter has

practically the same duration at Banff as at Glacier; the absolute maximum temperature at Banff (July 4, 1903) is recorded as 81.8.° The length of hot and cold seasons is approximately the same, and the range above freezing is practically the same.

Such differences as there are would favor a more rapid waste among the first type of glaciers. Occasionally midwinter temperatures above freezing would favor melting; the warm, dry Chinook winds would favor evaporation. Since, therefore, these glaciers are wasting with less rapidity than those of the second type, there must be some other cause than the temperature of the two regions.

Altitude of the snow-line.—In the Selkirks the snow-line is at an altitude of about 7,000 feet. From this level the glaciers descend with a fall of from 1,000 to 2,500 feet.

In the Rockies the snow-line is higher. It is variable, but is in general at an altitude of about 8,500 feet. The débris-covered glaciers end at a level of about 6,000 feet.

Topography.—The general effect of the occupation of a valley by a glacier is to round its outline, changing a V to a U in cross-section. The extent to which this can take place depends (1) upon the structure and character of the rock, and (2) upon the erosive capability of the glacier. The schists and quartzites of the Selkirks are readily rounded, and broad open U's produced in a relatively early stage of erosion. The result is the production of wide areas in which the accumulation of snow is possible. These gentle-sloped depressions aid the great precipitation and low snow-line in the production of the great névé regions.

The Rockies, in the region of the first type of glaciers, are composed for the most part of hard unmetamorphosed limestone, with vertical cleavage. Its tendency is, on weathering, to produce cliffs. The resulting valleys are steep-sided canyons even after their occupation by ice. Any widening out that takes place is below the snow-line, and impossible for névé formation. The small size and sluggish character of the glaciers may be effective of the same result.

The only points of lodgment for snow and ice are in cracks in the faces of cliffs, and here are found the only névés of the region, as feeders of the cliff glaciers. Thus precipitation, altitude of the snow-line, and topography combine to form great névés in the one

region; to prevent this formation, in the other. The result of this method of formation is that the valley glaciers on the east are entirely in the region of melting, and that the new snow supply they receive has no connection with their own forward movement.[1] It might therefore be expected that their rate of melting would be greater than that of the glaciers with great névé regions as reservoirs of accumulation. That this is not the case seems to be due entirely to the remaining factor of waste.

Amount of sunlight and of air received by the ice.—There are two causes which combine to shade the eastern glaciers: (1) shading by the steep cliffs, and (2) covering by débris. The shading by cliffs seems sufficient to determine the general position of the ice in its valley. This position of equilibrium once determined, the débris covering becomes the determining factor. That it is so is shown by the melting of the inter-débris areas, and its effectiveness is due to protection from both melting and evaporation.

GENERAL CONCLUSIONS

The type of glacier here described under the first group is not a common one, and probably exists only in regions of sharp relief and moderate precipitation. Less relief would afford opportunity for snow-fields to accumulate; greater snowfall would fill the valley, connecting the valley glacier with the cliff glaciers above, and so keeping the débris subglacial throughout. Either cause would produce a glacier of the second group—the ordinary type. Among glaciers of this ordinary type the concentration of débris on the surface at the lower end is a part of the process of retrogression, representing a stage of decadence.[2] The ice, if thus protected, is nearly stagnant, and the thickness at the lower end is relatively less than that of a vigorous glacier. This is clearly not the case with the glaciers of the first group; the ice is in motion, its slow movement coming from slight slope and slight pressure; the débris is superglacial; the thickness at the lower end is considerable, and the front

[1] Except in form these glaciers might properly be classed with Piedmont glaciers, which they strikingly resemble. See Russell, "Malaspina Glacier," *Journal of Geology*, Vol. I.

[2] I. C. RUSSELL, *American Geologist*, Vol. IX (1892), pp. 322–36.

is in some cases advancing. These facts show the glaciers to be vigorous and not in the last stages of decline.

The great changes in glaciers come as a response to climatic changes. Slight climatic oscillations take place in periods of about thirty-five years, and now is about the time when a glacial advance is expected. But the advance of these glaciers cannot be due to any such climatic change. Since the winds are deprived of their moisture by the mountains to the west, it is the western glaciers which should first respond to any such change. With the exception of the Asulkan the western glaciers mentioned are all rapidly retreating.

It would thus appear that the débris covering, and that alone, is responsible for the advance, and indeed for the continued existence, of the glaciers of the eastern Rockies.

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